Integrated Spectral Low Noise Image Sensor with Nanowire Polarization Filters for Low Contrast Imaging

Viktor Gruev
WASHINGTON UNIVERSITY THE

11/05/2015
Final Report

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
03-11-2015	FINAL REPORT	02/15/2011 - 08/15/2015

4. TITLE AND SUBTITLE
Integrated Spectral Low Noise Image Sensor with Nanowire Polarization Filters for Low Contrast Imaging

5a. CONTRACT NUMBER
FA9550-10-1-012

5b. GRANT NUMBER
66422

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Viktor Gruev

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
THE WASHINGTON UNIVERSITY
OFFICE OF SPONSORED RESEARCH SERVICES
1 BROOKINGS DR
SAINT LOUIS MO 63130-4862

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/PKS CODE
USAF, AFRL DUNS 143574726
AF OFFICE OF SCIENTIFIC RESEARCH
875 N. RANDOLPH ST. ROOM 3112
ARLINGTON VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Public release and distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Abstract: The research objective for this proposal is to develop a comprehensive program that will investigate and develop low noise imaging sensors capable of recording spectral and polarization information on the same chip and at the focal plane. I will use existing imaging sensor technology capable of recording spectral information, such as the Foveon X3 image sensor with vertically stacked photodiodes, as well as investigate alternative spectral imaging architectures based on my previous experience in this research area. I will develop nanowire polarization filters and investigate their integration with the spectral image sensors. In addition, I will investigate image processing algorithms that will take advantage of the spectral-polarimetric imaging sensor architecture and enable these sensors to be used for variety of applications that require real-time image processing. I will also investigate basic relationships between spectral and polarization information with intrinsic properties of objects, such as shape and material properties. I am proposing a comprehensive research program spanning several key areas:
1. Investigate the design and fabrication of a novel custom made imaging sensor with focal plane spectral detection capabilities.

15. SUBJECT TERMS
polarization imaging sensor, color-polarization imaging

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Viktor Gruev
UU	UU	UU	none		**19b. TELEPHONE NUMBER** (Include area code) 314.935.4465

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report

1. OBJECTIVES

The original objectives of the grants were:

- Investigate the design and fabrication of a novel custom made imaging sensor with focal plane spectral detection capabilities.
- Modeling of the electromagnetic wave interaction with aluminum nanowires structures to examine polarization properties for the proposed filter design.
- Investigate the design and fabrication of nanowires which exhibit polarization filtering capabilities.
- Investigate integration of CMOS spectral image sensor with aluminum nanowire polarization filters. Foveon image sensor and our novel custom made spectral image sensor will be integrated with polarization filters.
- Investigate application-based algorithms for the spectral-polarization image sensor.
- Investigating the relationship between polarization properties of light, spectral information, structure and shape of objects.
- Investigating adaptive processing techniques using spectral and polarization information of light.
- Investigating recovery of circularly polarization information of light using nanostrucutres in conjunction with spectral and linearly polarized light.

2. MAJOR ACCOMPLISHMENTS AND FINDINGS

2.1. Realization of spectral-polarization imaging sensor

Current division-of-focal-plane polarization imaging sensors can perceive intensity and polarization in real time with high spatial resolution, but are oblivious to spectral information. We present the design of such a sensor, which is also spectrally selective in the visible regime. We describe its extensive spectropolarimetric characterization. The sensor has a pixel pitch of 5 µm and imaging array of X by Y elements. Each element comprises spectrally sensitive vertically stacked photodetectors integrated with a 140 nm pitch nanowire linear polarizer. The sensor has SNR of 45dB, extinction ratio of ~3.5, QE of 12%, and linearity error of 1% in the green channel.

We have designed the sensor by the monolithic integration of pixelated nanowire linear polarization filters with a spectrally selective imaging array. The sensor can therefore simultaneously acquire spectral and polarization information in a scene with high spatial and temporal resolution. Furthermore, both spectral and polarization information is co-registered by virtue of the imaging sensor architecture. The sensor also has the benefits of being compact, lightweight and robust. The spectral and polarimetric capabilities of the integrated sensor have been thoroughly assessed using a carefully designed optoelectronic setup and are presented in this paper. The metrics used to evaluate the sensor are the following: quantum efficiency of the vertically stacked photodiodes, linearity of the pixel's output voltage, and signal-to-noise ratio (SNR).

More details on the spectral-polarization sensor can be found in the archived publication.

- M. Kulkarni and V. Gruev, "Integrated spectral-polarization imaging sensor with aluminum nanowire polarization filters," Optics Express, vol. 20, pp. 22997-23012, 2012.

2.2. Fabrication of nanowire pixelated polarization filters

We developed a procedure for fabricating a dual layer aluminum nanowire polarization filter suitable for division of focal plane polarization imaging sensors for the visible spectrum. The dual layer micropolarization array is fabricated using combination of optimized interference lithography and microfabrication steps resulting in a pixelated polarization filter array with 18 micron pitch and extinction ratios of 95 at 700nm incident light wavelength. The filter array is abutted to the surface of a custom CMOS imaging sensor and optical test are performed on the array.

The extinction ratios of the polarization filter arrays are evaluated at several different wavelengths. The maximum extinction ratio is achieved at longer wavelength, i.e. 700nm, and is 95. The minimum extinction ratio is achieved at shorter wavelength, i.e. 470nm, and is 51. The wavelength dependence of the nanowire polarization filters is an inherent property of the filters. If the width of the aluminum nanowires is decreased, the extinction ratios of the filter array can be improved as suggested by theoretical modeling.

More details on the nano-fabrication method for pixelated nanowire polarization filters can be found in the archived publication.

V. Gruev, "Fabrication of a dual-layer aluminum nanowires polarization filter array," Optics Express, vol. 19, pp. 24361-24369, Nov 21 2011.

2.3. Interpolation algorithms for division of focal plane imagers

We have developed several different interpolation algorithms for division of focal plane polarization sensors. We started with adapting first order algorithms to our sensor, such as bilinear, bicubic and gradient based interpolation algorithms. We later developed an interpolation algorithm using statistical methods.

Image interpolation and denoising are important techniques in image processing. These methods are inherent to digital image acquisition as most digital cameras are composed of a 2D grid of heterogeneous imaging sensors. Current polarization imaging employ four different pixelated polarization filters, commonly referred to as division of focal plane polarization sensors. The sensors capture only partial information of the true scene, leading to a loss of spatial resolution as well as inaccuracy of the captured polarization information. Interpolation is a standard technique to recover the missing information and increase the accuracy of the captured polarization information. Here we focus specifically on Gaussian process regression as a way to perform a statistical image interpolation, where estimates of sensor noise are used to improve the accuracy of the estimated pixel information. We further exploit the inherent grid structure of this data to create a fast exact algorithm that operates in $O\square N^{3/2}\_$ (vs. the naive $O\ N^3\_$), thus making the Gaussian process method computationally tractable for image data. This modeling advance and the enabling computational advance combine to produce significant improvements over previously published interpolation methods for polarimeters, which is most pronounced in cases of low signal-to-noise ratio (SNR). We provide the comprehensive mathematical model as well as experimental results of the GP interpolation performance for division of focal plane polarimeter.

More details about our interpolation methods can be found in the archived publication:

- S. K. Gao and V. Gruev, "Bilinear and bicubic interpolation methods for division of focal plane polarimeters," Optics Express, vol. 19, pp. 26161-26173, Dec 19 2011.

- S. Gao and V. Gruev, "Gradient-based interpolation method for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 1137-1151, 2013.

- E. Gilboa, J. Cunningham, A. Nehorai and V. Gruev, "Image interpolation and denoising for division of focal plane sensors using Gaussian Processes," Optics Express, vol. 22, Issue 12, pp. 15277-15291, 2014.

2.4. Calibration of division of focal plane sensors:

We have developed two calibration methods for division-of-focal-plane polarimeters. Typical division-of-focal-plane polarimeters for the visible spectrum employ nanowires in order to construct linear polarization filters. Mismatches in the size of the nanowires will lead to optical variations at the macro scale and we outline two calibration methods which mitigate these effects. Both methods were developed from the same linear model for polarization pixels, but one treats each pixel independently, and the other treats super-pixel groups together. We showed that the super-pixel approach is mathematically more powerful than the single-pixel approach and can correct both the typical photodetector gain and offset non-idealities in addition to polarization sensitive flaws such as non-ideal filter orientations and non-ideal filter diattenuation coefficients. The single-pixel approach can only correct for non-ideal gains and offsets.

The measurements of our visible-spectrum linear DoFP polarimeter show that a majority of the non-uniformity between pixels is in their gains and offsets, but a significant amount of variation occurs in the model parameters that the single-pixel approach cannot correct, including a constant rotational offset and moderate variations in filter diattenuations. Thus we have shown that calibrating each pixel independently reduces DoLP reconstruction errors from 12% to 10% for moderate light illuminations. Calibrating each super-pixel as a unit reduces the RMSE to approximately 1%. Similar reductions in error occur for reconstructing the intensity and AoP images. These figures indicate that the super-pixel calibration method is worth the extra computational effort, but there are still some un-addressed sources of error. These unaddressed sources of error include the image sensor's non-linear response, temporal noise, including the photon shot noise and readout noise, and the non-uniformities in the flat-field that the calibration apparatus produces.

Finally, we showed that though the calibration parameters were determined using a tungsten-halogen lamp for illumination with only an IR blocking filter in place, they performed well across the visible spectral range of the polarimeter. It is also worth noting that the optical properties of the polarimeter are stable enough that the same calibration parameters have been used with no measurable difference for about two years during the development of this work. The improvements in the quality of real-life images obtained from a division of focal plane polarimeter for the visible spectrum after applying the two calibration methods are also demonstrated in this paper.

More details about our calibration methods can be found in the archived publication:

- S. Powell and V. Gruev, "Calibration methods for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 21040-21056, 2013.

2.5. Opto-electronic evaluation of division of focal plane polarization imagers:

The development of high resolution division-of-focal-plane polarimeters in the visible spectrum allows real-time capture of two chief properties of interest, the degree of linear polarization and the angle of polarization. The accuracy of these two parameters can be influenced by a number of factors in the imaged scene, from the incident intensity and wavelength, to the lens used for image capture. The alignment, transmission, and contrast ratios of the pixel matched filters also impact the measured parameters. A system of measurements are presented here that show how these factors can determine the quality of a division-of-focal-plane polarimeter.

Visible spectrum DoFP polarimeters allow the estimation of the DoLP and AoP at high spatial and temporal resolution. A variety of factors, including the intensity, wavelength, and the optical path of the incident light influence the accuracy of this estimation. Presented here are a formal system of

experiments designed to quantify these effects for a DoFP sensor. The experiments give a complete picture of the estimation accuracy of the DoLP and AoP. They illustrate the effects that mismatched analyzer filters have on the accuracy of the DoLP and AoP estimation. They show how the estimations are functions of the spectrum of incident light, performing worse for shorter wavelengths, but remaining relatively constant over the broader visible range. They also demonstrate how important collimation is to reducing optical crosstalk, showing that light divergence is a key limitation to DoLP and AoP estimation. They measured that this degradation from divergence directly impacts the choice of lens, with narrower fields-of-view contributing less error. Finally, they show that the sensor is less accurate for lower intensities, due to a lowered SNR. The experiments presented here allow for an objective means to evaluate and compare DoFP polarimeters.

More details about our opto-electronic evaluation methods can be found in the archived publication:

- T. York and V. Gruev, "Characterization of a Visible Spectrum Division-of-Focal-Plane Polarimeter," Applied Optics, vol. 51, pp. 5392-5400, 2012.

2.6. Development of a bio-inspired polarization camera and applications to detecting neural activity:

We present recent work on bio-inspired polarization imaging sensors and their applications in biomedicine. In particular, we focus on three different aspects of these sensors. First, we describe the electro-optical challenges in realizing a bio-inspired polarization imager, and in particular, we provide a detailed description of a recent low-power CMOS polarization imager. Second, we focus on signal processing algorithms tailored for this new class of bio-inspired polarization imaging sensors, such as calibration and interpolation. Third, the emergence of these sensors has enabled rapid progress in characterizing polarization signals and environmental parameters in nature, as well as several biomedical areas, such as label-free optical neural recording, dynamic tissue strength analysis, and early diagnosis of flat cancerous lesions in a murine colorectal tumor model. We highlight results obtained from these three areas and discuss future applications for these sensors.

More details about our bio-inspired polarization sensor and its application to biomedical applications can be found in the archived publication:

- T. Charanya, T. York, S. Bloch, G. Sudlow, R. Tang, W. Akers, D. Rubin, V. Gruev, S. Achilefu, "Trimodal color-fluorescence-polarization endoscopy aided by a tumor selective molecular probe accurately detects flat lesions in colitis-associated cancer," Journal of Biomedical Optics, 2014.

- T. York, S. Powell, S. Gao, L. Kahan, T. Charanya, D. Saha, N. Roberts, T. Cronin, J. Marshall, S. Achilefu, S. Lake, B. Raman, and V. Gruev, "Bio-Inspired Polarization Imaging Sensors: From Circuits and Optics to Signal Processing Algorithms and Biomedical Applications," Proceedings of the IEEE, Vol. 102, No. 10, pp. 1450-1469, 2014.

- T. York, L. Kahan, S. Lake and V. Gruev, "Real-time high-resolution measurement of collagen alignment in dynamically loaded soft tissue," Journal of Biomedical Optics, vol. 19, no. 6, pp. 066011, 2014.

- Y. Liu, T. York, W. Akersa, G. Sudlowa, V. Gruev, and S. Achilefua, "Complementary Fluorescence-Polarization Microscopy using Division-of-Focal-Plane Polarization Imaging Sensor," Journal of Biomedical Optics, 2012.

2.7. Surface normal extraction using bio-inspired polarization sensor

The polarization properties of reflected light capture important information about the object's inherent properties: material composition, i.e. index of refraction and scattering properties, and shape of the object, i.e. surface normal. Polarization information therefore has been used for surface reconstruction

using a single-view camera with unpolarized incident light. However, this surface normal reconstruction technique suffers from a zenith angle ambiguity. In this paper, we have utilized circularly polarized light to solve for the zenith ambiguity by developing a detailed model using Mueller matrix formulism and division of focal plane polarization imaging technology. Experiment results validate our model for accurate surface reconstruction.

The contribution of this work is to exploit the phase information of light, i.e. circular polarization properties of light, to determine shape. The phase difference between the two orthogonal components of the light wave determines the elliptical component of the polarization state. Using the elliptical component of polarization, the ambiguity of the zenith angle in Fresnel's reflections can be resolved from a single viewpoint using a single imaging sensor. In addition this work applies the powerful concept of Stokes vectors and Mueller matrices to analyze more complex input light sources and derive a closed-form solution for both the zenith and azimuth angles. To solve for the azimuth ambiguity, this paper uses a reconstruction method based on the one presented in the literature. Furthermore, this paper employs a division of focal plane polarimeter capable of acquiring polarization information at every imaged frame with high spatial resolution. The imaging sensor is realized by monolithically integrating pixelated nanowire polarization filters with an array of pixels that use CCD technology.

More details about our 3-D surface normal extraction using polarization information can be found in the archived publication:

- N. Missael Garcia, I. de Erausquin, C. Edmiston, and V. Gruev, "Surface normal reconstruction using circularly polarized light," Optics Express, 2015.

2.8. Dynamic Polarization Signaling in Swordtails Alters Female Mate Preference

Polarization of light —and visual sensitivity to it—is pervasive across aquatic and terrestrial environments. Documentation of invertebrate use of polarized light is widespread from navigation and foraging to mate-recognition. In contrast, evidence for vertebrate use of polarized light is limited, and accounts of polarization communication by vertebrates are conspicuously missing. Here we investigate polarization-mediated communication by northern swordtails, *Xiphophorus nigrensis*, using a custom-built videopolarimeter to measure dynamic polarization signals and a novel experimental paradigm that manipulates polarization signals without modifying their brightness or color. We conducted mate choice trials in an experimental tank that illuminates a pair of males with light passed through a polarization and a diffusion filter. By alternating the order of these filters between males, we presented females with live males that differed in polarization features by > 100%, but with intensity and color differences below detection thresholds (<5%). Combining videopolarimetry and polarization-manipulated mate choice trials, we found sexually dimorphic polarized reflectance, polarization-dependent mate choice behavior, and differential polarization signaling across social contexts. Male swordtails exhibit greater polarization contrast than females, and females preferentially associate with high polarization-reflecting males. Males also adjust polarization signals based on social context by increasing within-body contrasts and decreasing body-to-background contrasts in social conditions relative to asocial conditions. Polarization cues in mate choice contexts may provide aquatic vertebrates with enhanced detection of specific display features (e.g., movements or angular information), as well as a dynamic signaling mechanism that may enhance detection by intended viewers while minimizing detection by others.

More details about our behavioral work using polarization information can be found in the archived publication:

- G. Calabrese, P. Brady, V. Gruev, and M. Cumming, "Polarization Signaling in Swordtails Alters Female Mate Preference," Proceedings of National Academy of Sciences, Vol. 111, No. 37, pp. 13397-13402, 2014.

3. PERSONAL SUPPORTED

The following individuals at Washington University in St. Louis were supported by this award:

1. Viktor Gruev, Associate Professor, Department of Computer Science and Engineering
2. Timothy York, PhD Students, Department of Computer Science and Engineering
3. Shengkui Gao, PhD Students, Department of Computer Science and Engineering
4. Missael Garcia, PhD Students, Department of Computer Science and Engineering

4. PUBLICATIONS:

Journal Publications:

1. N. Missael Garcia, I. de Erausquin, C. Edmiston, and V. Gruev, "Surface normal reconstruction using circularly polarized light," Optics Express, 2015.
2. T. Charanya, T. York, S. Bloch, G. Sudlow, R. Tang, W. Akers, D. Rubin, V. Gruev, S. Achilefu, "Trimodal color-fluorescence-polarization endoscopy aided by a tumor selective molecular probe accurately detects flat lesions in colitis-associated cancer," Journal of Biomedical Optics, 2014.
3. T. York, S. Powell, S. Gao, L. Kahan, T. Charanya, D. Saha, N. Roberts, T. Cronin, J. Marshall, S. Achilefu, S. Lake, B. Raman, and V. Gruev, "Bio-Inspired Polarization Imaging Sensors: From Circuits and Optics to Signal Processing Algorithms and Biomedical Applications," Proceedings of the IEEE, Vol. 102, No. 10, pp. 1450-1469, 2014.
4. G. Calabrese, P. Brady, V. Gruev, and M. Cumming, "Polarization Signaling in Swordtails Alters Female Mate Preference," Proceedings of National Academy of Sciences, Vol. 111, No. 37, pp. 13397-13402, 2014.E
5. E. Gilboa, J. Cunningham, A. Nehorai and V. Gruev, "Image interpolation and denoising for division of focal plane sensors using Gaussian Processes," Optics Express, vol. 22, Issue 12, pp. 15277-15291, 2014.
6. T. York, L. Kahan, S. Lake and V. Gruev, "Real-time high-resolution measurement of collagen alignment in dynamically loaded soft tissue," Journal of Biomedical Optics, vol. 19, no. 6, pp. 066011, 2014.
7. R. Njuguna and V. Gruev, "Current-Mode CMOS Imaging Sensor with Velocity Saturation Mode of Operation and Feedback Mechanism," IEEE Sensors Journal, vol.14, no.3, pp.710-721, 2014.
8. S. Powell and V. Gruev, "Calibration methods for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 21040-21056, 2013.
9. S. Gao and V. Gruev, "Gradient-based interpolation method for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 1137-1151, 2013.
10. T. York and V. Gruev, "Characterization of a Visible Spectrum Division-of-Focal-Plane Polarimeter," Applied Optics, vol. 51, pp. 5392-5400, 2012.
11. R. Njuguna and V. Gruev, "Low Power Programmable Current Mode Computational Imaging Sensor," IEEE Sensors Journal, vol. 12, pp. 727-736, Apr 2012.
12. Y. Liu, T. York, W. Akersa, G. Sudlowa, V. Gruev, and S. Achilefua, "Complementary Fluorescence-Polarization Microscopy using Division-of-Focal-Plane Polarization Imaging Sensor," Journal of Biomedical Optics, 2012.

13. M. Kulkarni and V. Gruev, "Integrated spectral-polarization imaging sensor with aluminum nanowire polarization filters," Optics Express, vol. 20, pp. 22997-23012, 2012.
14. V. Gruev, "Fabrication of a dual-layer aluminum nanowires polarization filter array," Optics Express, vol. 19, pp. 24361-24369, Nov 21 2011.
15. S. K. Gao and V. Gruev, "Bilinear and bicubic interpolation methods for division of focal plane polarimeters," Optics Express, vol. 19, pp. 26161-26173, Dec 19 2011.

5. INTERACTIONS

5.1 Conference participations:

The following conferences were participated in by members of the research team relevant to this research award:

1. SPIE Defense and Security Symposium, Baltimore MD, March 2012 and 2014

2. SPIE Polarization Science and Remote Sensing II, San Diego, CA August 2013.

3. SPIE Photonics West, San Francisco, 2012, 2013, 2014

4. IEEE Circuits and Systems Symposium (ISCAS), 2011-2015.

6. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None

7. HONORS/AWARDS

1. Best paper award at IEEE ISCAS 2015
2. Best paper award at IEEE ISCAS 2011
3. Best demo award at IEEE ISCAS 2014
4. Highest number of downloads from all Proceedings of IEEE papers published in 2014.

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

vgruev@wustl.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

314.935.4465

Organization / Institution name

Washington University in St. Louis

Grant/Contract Title
The full title of the funded effort.

Integrated Spectral Low Noise Image Sensor with Nanowire Polarization Filters for Low Contrast Imaging

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-10-1-0121

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Viktor Gruev

Program Manager
The AFOSR Program Manager currently assigned to the award

Kenneth Goretta

Reporting Period Start Date

02/15/2011

Reporting Period End Date

08/15/2015

Abstract

The research objective for this proposal is to develop a comprehensive program that will investigate and develop low noise imaging sensors capable of recording spectral and polarization information on the same chip and at the focal plane. I will use existing imaging sensor technology capable of recording spectral information, such as the Foveon X3 image sensor with vertically stacked photodiodes, as well as investigate alternative spectral imaging architectures based on my previous experience in this research area. I will develop nanowire polarization filters and investigate their integration with the spectral image sensors. In addition, I will investigate image processing algorithms that will take advantage of the spectral-polarimetric imaging sensor architecture and enable these sensors to be used for variety of applications that require real-time image processing. I will also investigate basic relationships between spectral and polarization information with intrinsic properties of objects, such as shape and material properties. I am proposing a comprehensive research program spanning several key areas:

1. Investigate the design and fabrication of a novel custom made imaging sensor with focal plane spectral detection capabilities.

2. Modeling of the electromagnetic wave interaction with aluminum nanowires structures to examine polarization properties for the proposed filter design.

3. Investigate the design and fabrication of nanowires which exhibit polarization filtering capabilities.

4. Investigate integration of CMOS spectral image sensor with aluminum nanowire polarization filters. Foveon image sensor and our novel custom made spectral image sensor will be integrated with polarization filters.

5. Investigate application-based algorithms for the spectral-polarization image sensor.

6. Investigating the relationship between polarization properties of light, spectral information, structure and shape of objects.

7. Investigating adaptive processing techniques using spectral and polarization information of light.

8. Investigating recovery of circularly polarization information of light using nanostrucutres in conjunction with spectral and linearly polarized light.

I believe that the proposed research will not only contribute to advancement of spectral and polarization imaging but also make significant advances in novel imaging architectures, integration of nanomaterials with CMOS technology and algorithm for spectral-polarization image processing. This fundamental work will have significant impact well beyond these topics by contributing to a whole host of new applications including security, unmanned vehicles and finger print detection, just to name a few.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

AFD-070820-035.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

report ver. 1.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

- N. Missael Garcia, I. de Erausquin, C. Edmiston, and V. Gruev, “Surface normal reconstruction using circularly polarized light,” Optics Express, 2015.

- T. Charanya, T. York, S. Bloch, G. Sudlow, R. Tang, W. Akers, D. Rubin, V. Gruev, S. Achilefu, “Trimodal color-fluorescence-polarization endoscopy aided by a tumor selective molecular probe accurately detects flat lesions in colitis-associated cancer,” Journal of Biomedical Optics, 2014.

- T. York, S. Powell, S. Gao, L. Kahan, T. Charanya, D. Saha, N. Roberts, T. Cronin, J. Marshall, S. Achilefu, S. Lake, B. Raman, and V. Gruev, “Bio-Inspired Polarization Imaging Sensors: From Circuits and Optics to Signal Processing Algorithms and Biomedical Applications,” Proceedings of the IEEE, Vol. 102, No. 10, pp. 1450-1469, 2014.

- G. Calabrese, P. Brady, V. Gruev, and M. Cumming, “Polarization Signaling in Swordtails Alters Female Mate Preference,” Proceedings of National Academy of Sciences, Vol. 111, No. 37, pp. 13397-13402, 2014.

- E. Gilboa, J. Cunningham, A. Nehorai and V. Gruev, “Image interpolation and denoising for division of focal plane sensors using Gaussian Processes,” Optics Express, vol. 22, Issue 12, pp. 15277-15291, 2014.

- T. York, L. Kahan, S. Lake and V. Gruev, “Real-time high-resolution measurement of collagen alignment in dynamically loaded soft tissue,” Journal of Biomedical Optics, vol. 19, no. 6, pp.

066011, 2014.

- R. Njuguna and V. Gruev, "Current-Mode CMOS Imaging Sensor with Velocity Saturation Mode of Operation and Feedback Mechanism," IEEE Sensors Journal, vol.14, no.3, pp.710-721, 2014.

- S. Powell and V. Gruev, "Calibration methods for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 21040-21056, 2013.

- S. Gao and V. Gruev, "Gradient-based interpolation method for division-of-focal-plane polarimeters," Optics Express, vol. 21, pp. 1137-1151, 2013.

- T. York and V. Gruev, "Characterization of a Visible Spectrum Division-of-Focal-Plane Polarimeter," Applied Optics, vol. 51, pp. 5392-5400, 2012.

- R. Njuguna and V. Gruev, "Low Power Programmable Current Mode Computational Imaging Sensor," IEEE Sensors Journal, vol. 12, pp. 727-736, Apr 2012.

- Y. Liu, T. York, W. Akersa, G. Sudlowa, V. Gruev, and S. Achilefua, "Complementary Fluorescence-Polarization Microscopy using Division-of-Focal-Plane Polarization Imaging Sensor," Journal of Biomedical Optics, 2012.

- M. Kulkarni and V. Gruev, "Integrated spectral-polarization imaging sensor with aluminum nanowire polarization filters," Optics Express, vol. 20, pp. 22997-23012, 2012.

- V. Gruev, "Fabrication of a dual-layer aluminum nanowires polarization filter array," Optics Express, vol. 19, pp. 24361-24369, Nov 21 2011.

- S. K. Gao and V. Gruev, "Bilinear and bicubic interpolation methods for division of focal plane polarimeters," Optics Express, vol. 19, pp. 26161-26173, Dec 19 2011.

Changes in research objectives (if any):

None

Change in AFOSR Program Manager, if any:

Original program manager: Dr. Kitt Reinhardt
2nd program manager: Dr. James Hwang
3rd program manager: Dr. Kenneth Goretta

Extensions granted or milestones slipped, if any:

6 months non cost extension.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Nov 03, 2015 22:26:41 Success: Email Sent to: vgruev@wustl.edu